Heavy reflector experiment in the IPEN/MB-01 reactor

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Abstract

This experiment performed in the IPEN/MB-01 research reactor facility is devoted to the measurements of physical parameters of a light water core surrounded by a stainless steel reflector. Several plates of SS-304 (3 mm thick) were introduced in the west face of the core of the IPEN/MB-01 reactor. The experimental results comprise several measured quantities such as: critical control bank positions, reactivity and relative power density distribution as a function of the number of SS-304 plates. The experimental results show clearly the competition between neutron absorption and neutron reflection in the SS-304 plates. The theoretical analysis was performed in a twofold independent approach. CEA/Cadarache used the Monte Carlo code TRIPOLI4 with JEFF3.1 library to analyse the experimental data while IPEN used the coupled NJOY/AMPX-II/TORT with ENDF/B-VI.8 and MCNP-5 with ENDF/B-VII.0. All calculation methodologies show applicability to describe the physics involved in the heavy reflector system. The quality of the recently released new nuclear data libraries (JEFF3.1 and ENDF/B-VII.0) was addressed and it was shown that these new data have a better quality than older libraries such as ENDF/B-VI.8.

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1. Introduction

Water reflector and SS baffle reflector (about 1 or 2 cm thick) are commonly used in (experimental and industrial) LWRs. However, they do not present the best neutron's characteristics in terms of neutron savings, i.e. economy of fissile material, contrary to SS heavy reflector (about 10 cm thick) that enables to limit the radial leakage, in particular by back scattering the fast neutrons to the core. The major awaited improvements of such a reflector are:

- a better reflector savings, i.e., an economy in fissile material,
- an optimised radial power distribution,
- the reduction of fast fluence to the vessel, leading to a plant life extension.

The purposes of this work are to present the effect of a SS reflector on several configurations, and to make a brief experimental validation of

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Monte-Carlo and deterministic calculations, on these configurations, with the latest nuclear data libraries available. The experiment presents a SS-304 reflector with a varying thickness at the IPEN/MB-01 Research Reactor Facility. Several plates of SS-304 (3 mm thick) were introduced as SS reflector in the west face of this reactor and several quantities such as critical control bank configuration, reactivities, and relative power density distributions were measured as a function of the number of plates. A total of 32 plates were used in the experiment which gave a total thickness of around 9.6 cm. Competition between the effect of thermal neutron capture by SS and the effect of fast neutrons back scattering to the core is highlighted by varying SS reflector thickness. The capture is preponderant for small thicknesses of SS (about 1 or 2 cm), whereas scattering effect increases with the SS thickness (in particular, the mean free path for fast neutron in SS in relationship with the inelastic scattering reaction is more than 10 cm). The theoretical analysis was performed employing TORT (Rhoades, 1997), MCNP-5(X-5 Monte Carlo Team, 2003) and TRIPOLI4 [Both, 1994] computer codes using recently released nuclear data libraries.

2. The heavy reflector experiment set up

The reactor core setup for this experiment employs the standard 28x26 4.3% enriched UO2 fuel rod array configuration and it is shown in Fig. 1. A complete core description of the IPEN/MB-01 core can be found in (Dos Santos et. al. 2004). The control bank (BC) at the upper right corner is named BC1 while the one at lower left corner is named BC2. The columns of the IPEN/MB-01 core configuration are identified by numbers ranging from 00 to 29 while the lines are identified by letters as shown in Fig. 1. This is an important aspect in order to identify the fuel rod location in the core.

A mechanism was specially designed and mounted at the west face of the IPEN/MB-01 core to hold and fix the SS-304 plates in the reflector region. Figure 2 is a mock-up made of wood specially built with the purpose to show the details of the supports of the whole set up and the location of the plates relative to the core. The supports are made of stainless steel and they are fixed in the frames of the facility. A maximum weight of 300 kg was allowed in the experiment. This is the reason why a maximum of 32 plates were used. The distance between the active core (last row of fuel rods in the real case) and the plates is controlled by the screws shown in Fig. 2. There are four of them: two in the face shown in Fig. 2, and two on the back side. Figure 2 also shows a polyethylene disk. This disk is connected to two wheels designed to compress the plates tightly together. The innermost wheel compresses the plates and the second rotates in the opposite direction to tighten everything together. Figure 3 shows a front view of the plates with the core location and several other details.

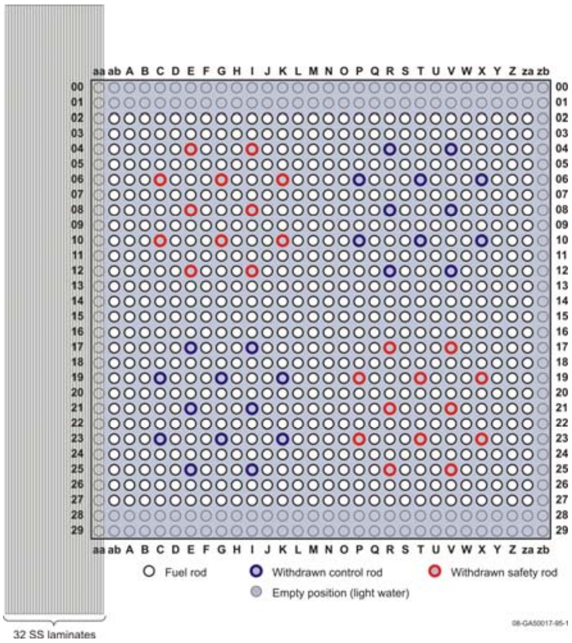

Fig. 1. Experimental core configuration.

This whole experimental set up was mounted in the IPEN/MB-01 core. The chosen distance between last fuel rod row and the first plate was 5.5 ± 1.0 mm. The reactivity inserted by the compress disk and the plate support were measured and were equal to 5.5 pcm; a small effect that may be neglected in the theoretical analysis.

The chemical composition, material density and several geometric quantities of the plates were all measured at IPEN.

Fig. 2. The heavy reflector experiment mock-up.

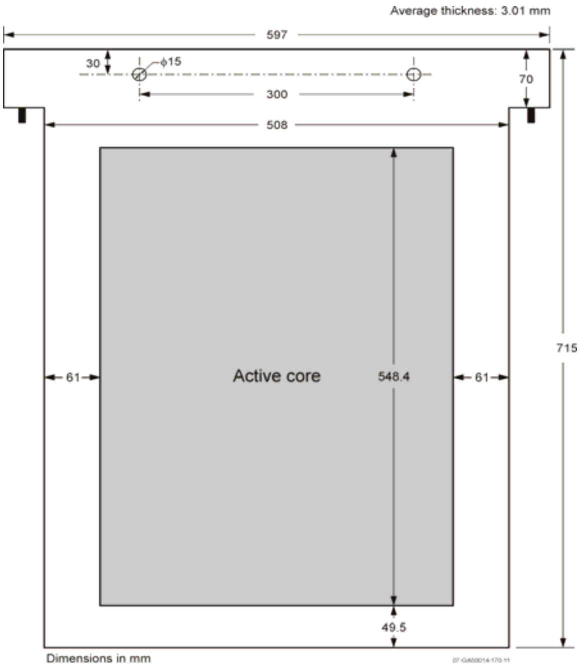

Fig. 3. Front view of the experiment set up.

3. The experiment results

During the execution of the experiment, the safety rods were kept in the total withdrawn position. The quantities: a) critical control bank positions for both BC1 and BC2 at the same withdrawn level and for BC1 fixed at 58.12% and BC2 allowed to vary to reach criticality, b) reactivity and c) relative fission density distribution through the measurements of ^{143}Ce activity by a gamma scanning equipment, were all measured as a function of the number of SS-304 plates.

Table 1 shows the measured reactivity and the critical control bank position as a function of the number of plates. The uncertainties are 3% for the reactivity and 0.013% for the critical positions. The first column represents the number of plates; the second one is the critical position for both control banks at the same withdrawn position; the third one is the measured reactivity; the fourth one is the reactivity variation and the fifth one is the critical BC2 control bank position for BC1 fixed at 58.12% withdrawn position. Table 1 shows that the reactivity decreases up to the sixth plate and after that it increases and becomes nearly zero (condition of zero plates) for the 21 plates case and reaches a value of 164.5 pcm when the 32 plates are inserted in the reflector. This is a very striking result because it demonstrates that when all 32 plates are inserted in the reflector there is a net gain of reactivity. The reactivity behaviour demonstrates all the physics events already mentioned in this work. When the number of plates are small (around 6), the neutron absorption in the plates is more important than the neutron reflection and the reactivity decreases. This condition holds up to a point where the neutron reflection becomes more important than the neutron absorption in the plates and the reactivity increases. The neutronic importance of a thermal neutron scattered back to the core by a water reflector is larger (in term of ability for fuel fission) than a fast neutron. However, a lot of fast and epithermal neutrons are also scattered back through SS, and this compensates their small neutron importance. It can even explain why a positive reactivity effect is observed for a number of plates superior to 24.

Table 2 shows the relative fission rates across column 14. The data were measured by a gamma scanning equipment and normalized to the fuel rod placed in the position M14. The measurements were performed for the condition without plates and for the conditions when 21 and 32 plates were inserted in the reflector. The case of 21 plates was chosen because it gives a reactivity nearly equal to the case without plates, and the case of 32 plates because this is the maximum number of plates inserted in the moderator. The interesting part of the experimental results is the removal of the effect of the thermal peak in the fuel rods close to the reflector region, as expected. When the SS-304 plates are absent, the fission rate goes up in the last fuel rods close to the interface. This aspect is not present when the SS-304 plates are inserted in the reflector region. Also, it can be noted, by comparing the cases with 21 and 32 plates, and going to the border of the active core that there is a slight increase of the fission density for the case of 32 plates, thus showing the effect of the neutron reflection when more plates are inserted in the reflector.

Table 1
Inserted reactivity and critical control bank position as a function of the number of plates

Nº Pla-tes	BC1=BC2 (%)	ρ (pcm)	$\Delta\rho$ (pcm)	BC2 (%) (BC1 fixed at 58.12 %)
0	58.12	0	---	58.12
1	60.90	-280.0±8.0	-280.0	63.95
2	61.87	-368.0±11.0	-94.0	66.21
3	62.30	-413.0±12.0	-41.0	67.22
4	62.43	-428.0±13.0	-13.0	67.35
6	62.16	-404.0±12.0	32.0	66.90
7	61.86	-373.0±11.0	29.6	66.16
8	61.54	-343.0±10.0	30.5	65.47
9	61.32	-322.0±10.0	21.5	64.94
11	60.74	-266.0±8.0	56.5	63.64
13	60.06	-200.0±6.0	66.5	62.18
15	59.55	-148.0±4.0	49.0	61.08
18	58.80	-71.0±2.0	75.0	59.53
21	58.16	-4.3±0.1	66.0	58.22
24	57.59	55.0±2.0	59.0	57.07
28	56.98	118.5±4.0	64.0	55.90
32	56.56	164.5±5.0	44.5	55.04

Table 2
Relative fission rates across column M14

Fuel Rod	0 Plates	21 Plates	32 Plates
ab14	0.68±0.01	0.35±0.01	0.37±0.01
B14	0.59±0.01	0.56±0.01	0.60±0.01
D14	0.68±0.01	0.69±0.02	0.71±0.01
F14	0.85±0.02	0.82±0.02	0.83±0.02
H14	0.93±0.02	0.88±0.02	0.91±0.02
I14	0.96±0.02	0.94±0.02	0.92±0.02
M14	1.00±0.02	1.00±0.02	1.00±0.02

4. Theoretical analysis of the heavy reflector experiment

4.1. The geometric model of the IPEN/MB-01 core and recommended uncertainties for the theoretical analysis

The geometrical model employed in all analysis follows the simplified geometry described in (Dos Santos, 2004). The uncertainties assigned to k_{eff} of critical configurations are those arising from the experimental data and from the geometric and material data of all components of the IPEN/MB-01 core. Critical configurations of the IPEN/MB-01 core based on the heavy reflector experiments but for the condition of all control banks in the withdrawn position were evaluated in (Dos Santos, 2008). The uncertainties assigned to k_{eff} in this evaluation can be applied straightforward to the heavy reflector experiment described in the present work. Combining the geometric and material uncertainties and the experimental uncertainty, a total uncertainty (σ_t) is obtained as 62.3 pcm. Furthermore, because thermocouples, control and instrumentation tubes, compress disk and laminate support are not included in the geometrical model, the total of their measured reactivity effect (-39.0 pcm) is included as a bias to k_{eff} of the geometric model (12.5 pcm for omitting thermocouples, 21 pcm for omitting neutron detectors, 5.5 pcm for the compress disk and laminate support).

4.2. The coupled system NJOY/AMPX-II/TORT

The nuclear data libraries employed in the coupled system NJOY/AMPX-II/TORT (Dos Santos et. al. 2000) were prepared using NJOY 99.90 (MacFarlane, 2000). The RECONR, BROADR, UNRESR, THERMR and GROUPR modules of NJOY were used in order to reconstruct and to Doppler broaden the cross sections, to calculate the self-shielding effects in the unresolved resonance region, to build the scattering matrices in the thermal region, and to transform these data into multigroup parameters, respectively. The pointwise and fine multigroup cross sections produced in the previous step were transferred to AMPX-II (Greene, 1984) by two in house interface modules AMPXR and BRDROL. The self-shielding treatment of the actinide resolved resonances in the neutron energy region from 0.625 eV to 5.53 keV was carried out by ROLAIDS and the neutron spectra in the several regions of the IPEN/MB-01 reactor by XSDRNPM. Firstly, XSDRNPM considered an infinite array of fuel pin cells. The k_{inf} spectral calculations were performed in the fine group structure considering a white boundary condition at the outer boundary of the cylindrized cell. The cross sections are homogenized at the fine group level. Next, these data are merged with those of other regions such as radial, top and bottom reflectors and so on. Finally, XSDRNPM considers radial and axial slices of the IPEN/MB-01 reactor to get the final spectra for the broad group collapsing. The broad group cross sections of the control rods, guided tube, and control rod bottom plugs were obtained using a super-cell model. At this point, the cross section library is problem dependent. The fine multigroup structure considered 620 groups (SAND-II structure). This set of fine multigroup cross sections were collapsed to 16 broad groups with fine groups in the thermal region (E<0.625 eV.). The order of scattering (Legendre order expansion) was P_3 throughout the analyses. Finally, the broad group library is conveniently formatted to the TORT (Rhoades, 1997) (3D Discrete Ordinates Code) format using the GIP (Rhoades, 1975) program. Subsequently, TORT performed k_{eff} and the flux calculations using the cross section libraries generated before, considering a fully tri-dimensional geometric modeling of the IPEN/MB-01 reactor core. The RECONR and BROADR modules of NJOY were run with 0.2 and 0.1 % interpolation tolerance, respectively, for all nuclides. The thermal neutron scattering files $S(\alpha,\beta)$ needed for hydrogen bound in water were obtained with LEAPR module of NJOY. These neutron scattering files have not been updated since ENDF/B-III evaluation (Koppel 1978) and the LEAPR module provides the NJOY users with an opportunity to create these data for the proper conditions (temperature, for example) for the computational analyses. The fully three dimensional geometric setup for the TORT calculations was considered with the X-Y-Z geometry, P_3 approximation, angular quadrature S_{16}, and a set of 16 groups considering 5 groups in the thermal region.

4.3. MCNP-5/ENDF-BVII.0

MCNP-5 was employed for the analyses of the heavy reflector experiment. MCNP-5 considered a very well detailed geometric model of the IPEN/MB-01 and the heavy reflector region. Its cross section library was generated by NJOY 99.259. SS nuclear data (Fe, Cr, Ni) in ENDF/BVII.0 are the same as ENDF/BVI.8 (ENDF/BVI.1 for Fe56 cross sections)

4.4. TRIPOLI4 / JEFF3.1

Calculations on IPEN/MB-01 experiments with a SS reflector were also performed with the French Monte-Carlo code TRIPOLI4: reference 3D continuous-energy calculations were made with the latest European nuclear data library, JEFF3.1 [NEA, 2006]. SS main compounds (Fe, Cr, Ni) were re-evaluated in JEFF3.1 library. Iron evaluation is based on measurements (total, elastic and inelastic cross sections, in the nineties) with a high resolution, more recent than ENDF/B-VII.0. The geometrical model corresponds to the simplified geometry described in (Dos Santos, 2004).

5. Theory/experiment comparison

Figure 4 shows the measured and calculated inserted reactivity reactivity (statistical uncertainty of 10 pcm at one standard deviation for Monte-Carlo calculations) as a function of the number of the SS-304 plates placed in the reflector. The calculated results are from TORT, MCNP-5 and TRIPOLI4. TORT employs only ENDF/B-VI.8 while MCNP-5 uses ENDF/B-VI.8 and ENDF/B-VII.0. As shown in Fig. 4, TORT overestimates the calculated reactivities. The main reason for that as will be seen shortly is the keff-bias considering the IPEN/MB-01 core without and with the SS-304 plates. The self-shielding effects in the SS-304 plates are not considered in the analysis. This aspect might introduce some discrepancies in the final TORT reactivities. Contrary to that, also as shown in Fig. 4, MCNP-5 results reproduce well the experimental data for both library used. However, it would be better to use a more detailed geometrical modelling for Monte-Carlo calculation: geometrical bias of modelling highlighted in paragraph 4.1 could depend on the thickness of the SS reflector (in particular, streaming effect in neutron detectors). The TRIPOLI4/JEFF3.1 core reactivity in the configuration with a water reflector is overestimated by 93 pcm ±7 (1σ), that is consistent with the trend of UOX core calculations got with JEFF3.1 [Litaize, 2006]. The TRIPOLI4/JEFF3.1 calculations show a systematic bias on SS reactivity worth (about 50 pcm), that is rather consistent with MCNP/ENDF/B-VII.0 calculation up to the configuration with 7 plates (small thickness of SS). Iron capture cross section is the same in both libraries, ENDF/B-VII.0 and JEFF3.1 that could explain the consistency in the trend of reactivity worth underestimation (up to 6 plates).

MCNP/ENDF/B-VII.0 and TRIPOLI4/JEFF3.1 calculations are not completely consistent for a larger thickness of SS (from 8 plates). It could be explained with a nuclear data effect and a geometrical modelling effect.

The iron elastic and inelastic cross section is different for the 2 evaluations, in term of level and shape (fluctuations were integrated in JEFF3.1 to take into account self-shielding effect) ; however, it is important to kept in mind that the Fe inelastic smooth cross section presents a large uncertainty (more than 10% at one standard deviation).

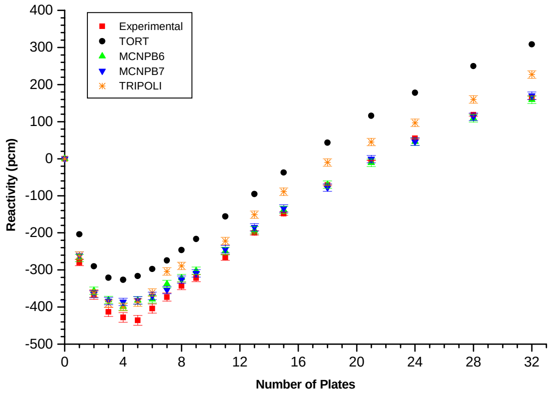

Fig. 4. Calculated and experimental reactivity as a function of the number of ss-304 plates.

Table 3 gives the k_{eff} calculated by TRIPOLI4 using JEFF3.1 for the critical configurations considering the control banks BC1 and BC2 at the same withdrawn level. These calculations were performed at CEA/Cadarache. Table 3 also shows the same quantity calculated by MCNP-5 with ENDF/B-VII.0 and TORT with ENDF/B-VI.8; both performed at IPEN. The analyses performed at IPEN with ENDF/B-VII.0 use the thermal scattering law from ENDF/B-VI.8. According to Oblozinsky (Oblozinsky, 2006) and also to several analyses performed at IPEN, the new thermal scattering law introduced in ENDF/B-VII.0 overpredicts the critical keff by around 100 pcm.

As shown in Table 3, TRIPOLI4 and MCNP-5 employing the recently released new libraries; respectively JEFF3.1 and ENDF/B-VII.0, reproduce rather well the critical eigenvalues with a SS reflector (iron nuclear data are enhanced with a large uncertainty) in relationship with the calculation of the water reflector configuration.

Table 3
MCNP-5 ,TORT and TRIPOLI4 k_{eff} results for the critical control bank configurations (BC1=BC2)

Number of plates	Keff TRIPOLI4 (JEFF3.1 20°C) 1σ =7pcm	Keff MCNP-5 (ENDF/B-VII.0 20°C) 1σ =7pcm IPEN	Keff TORT (ENDF/B-VI.8 20°C) IPEN
0	1.00093	1.00065	0.99530
1	1.00112	1.00080	0.99636
2	1.00098	1.00077	0.99655
3	1.00115	1.00095	0.99669
4	1.00121	1.00110	0.99678
5	1.00141	1.00112	0.99695
6	1.00136	1.00106	0.99679
8	1.00147	1.00078	0.99671
11	1.00137	1.00100	0.99665
13	1.00142	1.00072	0.99670
15	1.00152	1.00090	0.99668
18	1.00154	1.00079	0.99654
21	1.00142	1.00080	0.99657
24	1.00135	1.00072	0.99652
28	1.00134	1.00069	0.99651
32	1.00155	1.00086	0.99647

TORT k_{eff} results are underpredicted by around 350 pcm which is very consistent to several benchmark analyses [Van der Mark et. al. 2003] performed with ENDF/B-VI.8. According to Table 4, the k_{eff} calculated by TORT shows a bias of around 100 pcm considering the case without plates and with plates. This bias explains for most part the overprediction of the reactivity calculated by TORT as shown in Fig. 4.

The theory/experiment comparison for the fission rate distribution along column M14 is shown in Fig. 5, 6, and 7 for the condition without plates, 21 plates and 32 plates, respectively. The calculated results are only from TORT and ENDF/B-VI.8. The calculated fission rates generally agree rather well with the experimental values. As mentioned, the interesting aspect is the disappearance of the thermal flux peak effect in the fuel rods close to the reflector when the SS-304 plates are inserted. This detail is shown in Fig. 6 and 7.

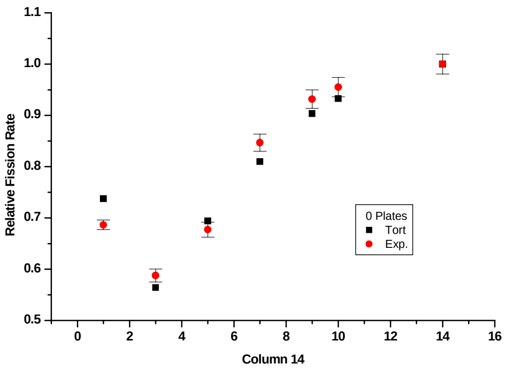

Fig. 5. Calculated and experimental fission rate distribution along column 14 without plates.

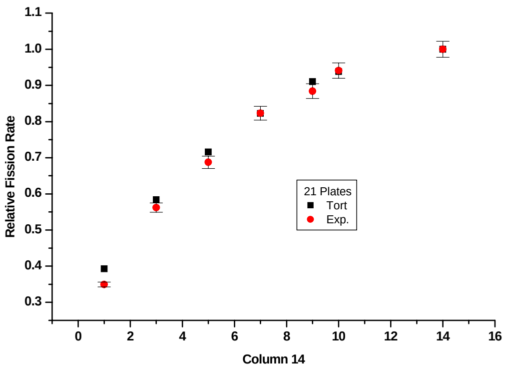

Fig. 6. Calculated and experimental fission rate distribution along column 14 for 21 plates.

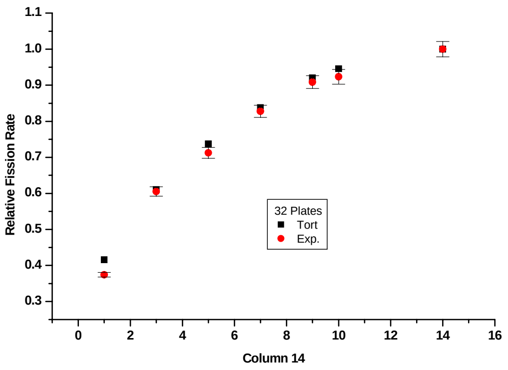

Fig. 7. Calculated and experimental fission rate distribution along column 14 for 32 plates.

6. Conclusions

Stainless Steel reflector characteristics on a UO2 core, both in terms of reactivity (i.e. reflector savings) and power distribution, was investigated experimentally in the IPEN/MB-01 research reactor.

The experiment performed in the Facility,, which consisted in introducing increasing thickness of SS plates on a side of the core, was successfully completed and analyzed. The reported experimental data are of high quality and can be very valuable to validate methodology and nuclear data libraries currently employed in LWR designs with heavy reflector. The competition between thermal neutron absorption and fast neutron reflection in the SS-304 plates was demonstrated experimentally. Interpretation has been performed by using employing TRIPOLI4/JEFF-3.1 and MCNP-5/ENDF-BVII.0, as TORT/ENDF-BVI.8.

All calculation methodologies demonstrate their capability to describe the physics involved in such a heavy reflector system. TORT shows a systematic overprediction of the reactivity inserted by the SS-304 plates. Also, some concerns may still have to be addressed in the deterministic case such as the self-shielding effects in the SS-304 plates. The fission density distribution even though performed in a single line in general was well predicted by TORT.

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